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COMPUTATIONAL METHODS FOR DETERMINING THE EFFECT OF STRESS ON CUTTING QUALITY[1]

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The characteristics of the residual stresses arising in float-glass production are presented. The forms, causes, magnitude and direction of the stresses are described. The condition for off-cut breakage is derived mathematically. Modeling with ANSYS Structural Ver. 14.0 is used to obtain the stress pattern when the breaking bar is raised and the critical parameters for which glass losses occur during cutting are determined.

Key words: mechanical roller cutting, residual stresses, off-cut break, cutting losses, ANSYS Structural 14.0.

Off-cut breakage and cutting losses are among the main problems arising when sheet glass is cut by the mechanical roller method. The reasons for these problems could lie with the cutting equipment (wear or incorrect adjustment) as well as the properties of the glass (high residual stresses in the glass play the main role here).

Until now the effect of the residual stresses in glass on the cutting process has not been studied fully. Previously, the maximum magnitude of the layer-wise stresses (irrespective of the glass thickness) was regulated in Russian standards documents (for example, GOST 111). However, the effect of membrane stresses, which have a large effect on the cutting, was neglected.

At the same time the leading global manufacturers of sheet glass have internal norms for monitoring membrane stresses. However, these norms are based on practical experience. As a result they are not universal. As a rule they are limited to a particular production line and, as practice shows, adherence to these norms does not eliminate cutting problems.

In the present article we describe a computational approach that can be used to establish better substantiated and general requirements for the residual stresses in sheet glass.

Description of Residual Stresses in Float Glass

In general, two types of residual stresses form in float glass — layer and membrane.

Layer stresses are formed as a result of the nonuniformity of the cooling of surface and inner layers. Layer stresses are proportional to the rate of cooling of float-ribbon and are distributed parabolically over the thickness of a sheet [1].

Layer stresses are oriented parallel to the surface of the glass. Since the sag of each elementary volume of the glass in the course of cooling of a float ribbon is uniform along all directions, layer stresses are the same along and across the pull line (excluding the edge zone).

Membrane stresses are formed as a result of the nonuniformity of cooling along the length and width of a float ribbon. Most important is the nonuniformity of cooling along the width of a float ribbon due to two main factors — the edge effect [2] and the longitudinal arrangement of the cooling heat-exchangers in the lehr. As a result several longitudinal bands, which cool at somewhat different rates, are formed in the float ribbon. The first bands to cool down to a temperature below the softening temperature keep the neighboring longitudinal bands of the float ribbon from shrinking, and correspondingly the membrane stresses are directed mainly along the pull line.

The transverse shrinkage of a float ribbon in the critical cooling zones (where the residual stresses are embedded) is relatively small, and for this reason the membrane stresses directed across the pull line are much lower.

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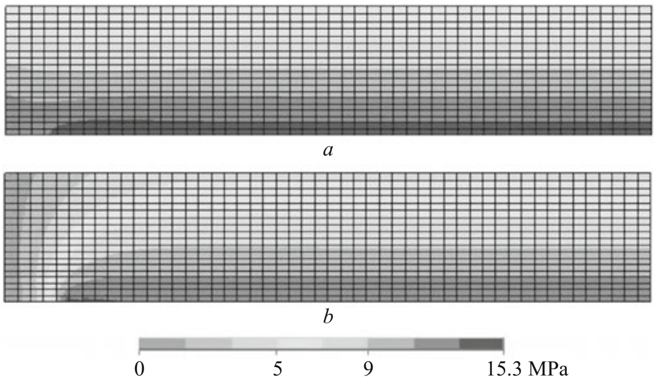

Fig. 1. Distribution of the stresses σ_x (*a*) and σ_y (*b*).

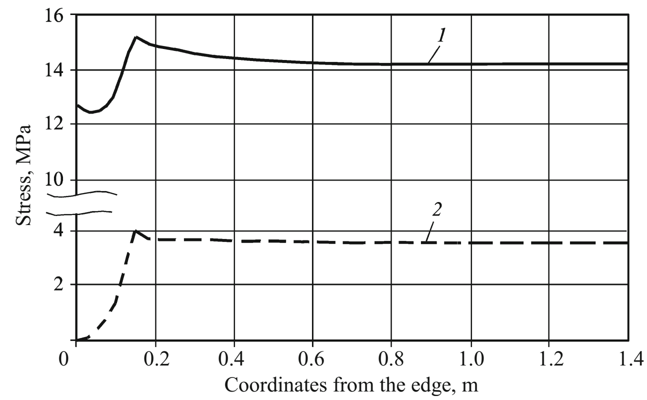

Fig. 2. Profile of the magnitude of the stresses σ_x (*1*) and σ_y (*2*) along the cutting axis.

The stresses along the glass thickness are taken to be zero because the absolute magnitude of the shrinkage in this direction is very small.

Membrane stresses have a complex distribution [3]. Their dispersion is much larger than that of layer stresses. The planes of the membrane and layer stresses coincide, and the stress state at each point is determined by their superposition.

Off-Cut Breakage

Off-cut breakage is a departure of the crack from the cutting line at the moment of breakage (as a rule, on cutting tables breakage is done by raising a breaking bar).

To calculate the stresses arising during breakage the problem of the change in the stresses at the moment an elastic isotropic sheet is raised by the bar was formulated. The modeling was done using the ANSYS Structural Ver. 14.0 software.

The following coordinate system was used in the model: the x axis is oriented in the same direction as the long edge of the sheet, the y axis along the short edge of the sheet and z axis along the thickness of the sheet.

The pattern of the principal stress vectors in the central part of the sheet at the moment the bar is raised by 20 mm was obtained: the stresses are proportional to the height to which the bar is raised; they reach their maximum values at the location of the contact with the sheet and decrease away from there. The contours of the stresses σ_x and σ_y in the glass sheet are presented in Fig. 1.

The following conclusions can be drawn from an analysis of the computational results (see Figs. 1 and 2):

– the principal axes of the stresses arising when the bar is raised coincide with the coordinate axes used in the model, i.e., they are oriented along the edges of the sheet;

– raising the bar generates virtually no stresses along the vertical axis (these stresses are not shown in the figures); this agrees with the notions about bending of thin plates [4];

– the profile of the stresses along the break axis (Fig. 2) is characterized by a pronounced edge effect.

It is evident that the stresses at a point far from a free edge in perpendicular directions are proportional, following Poisson's law according to which deformation along one axis gives rise to deformation (stress) along the second axis. The coefficient of proportionality is Poisson's ratio, which corresponds to the condition under which a planar deformed state arises.

The stresses in the central section, which determine the breakage process, are a superposition of the residual and bending components. In the regions where the bending stresses are superposed on the residual tensile stresses rupture starts sooner, before the total bending stresses reach the ultimate strength.

The propagation direction of an advancing crack is given in a manner where the crack front is perpendicular to the maximum tensile stresses [5]. If a propagating crack reached regions where the bending stresses are compensated by residual compression stresses, or regions with high local residual stresses oriented at an angle relative to the bending stresses, the crack can stop or the front can turn in an arbitrary direction.

Mathematically, the condition for an off-cut break for a transverse cut (break) is written as follows:

$$\sigma_x^{b} + \sigma_x^{mem} + \sigma_x^{lay} \le \sigma_y^{b} + \sigma_y^{mem} + \sigma_y^{lay}, \qquad (1)$$

where σ_x^{b}, σ_x^{mem} and σ_x^{lay} are, respectively, the bending, membrane and layer stresses along the sheet and σ_y^{b}, σ_y^{mem} and σ_y^{lay} are, respectively, the bending, membrane and layer stresses across the sheet.

In other words, the maximum stresses along the break axis must exceed the maximum stresses across it.

The tensile stresses reach maximum values on the top side of the sheet, since the bending component on it makes the largest contribution.

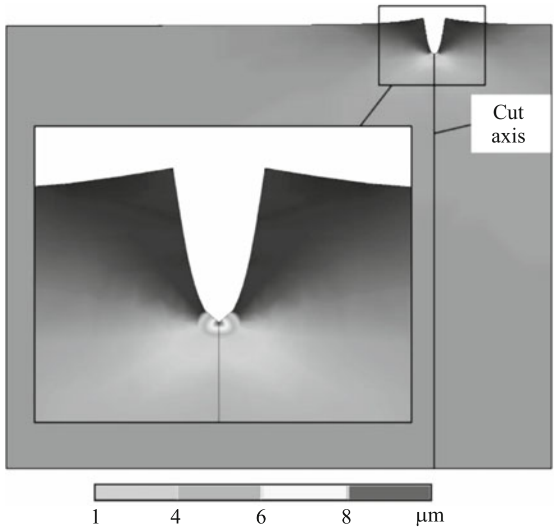

Fig. 3. Distribution of the displacements near a crack under a uniform tensile load.

For sections located away from the free edge the stresses σ_x^b and σ_y^b are proportional to one another:

$$\sigma_y^b = \mu\sigma_x^b, \tag{2}$$

where μ is Poisson's ratio.

The layer stresses are the same in all directions. This makes it possible to contract the expression (1):

$$\sigma_x^b(1-\mu) \le \sigma_x^{mem} - \sigma_y^{mem}. \tag{3}$$

The quantity $\sigma_x^{mem} - \sigma_y^{mem}$ is the difference of the residual membrane stresses acting along the x and y axes. This quantity can be determined directly by a polarization optical method (measuring across the glass thickness, for example, using Senarmont polarimeters).

The quantity σ_x^b (bending strength of the glass) can also be determined experimentally (for example, for small samples by the three-point bending method). This quantity is constant for a regime where the initial defect is formed.

The condition (3) can be satisfied in the case of high compression stresses along the glass sheet. This has been confirmed experimentally in [2].

As one can see from the expression (3) layer stresses have no effect on the turning of a crack, since they are the same in all directions. However, if the layer stresses are high, the surface layers of the sheet are in a strongly compressed state, as a result of which the bending strength of the glass, determined by the tensile stresses, increases but then the breaking force must be increased (the bar is raised higher), which impacts break quality negatively. For this reason, layer stresses must be limited in order to increase the cutting quality. The effect of layer stresses on the break quality depends strongly on the thickness of the glass.

The conditions on the edge zone of a float ribbon are special. Since the normal stress on the free surface of the body is zero, i.e., σ_y^b and $\sigma_y^{mem} = 0$, even if the compression stresses along the glass edges σ_x^{mem} are much higher than at the center of the glass, the conditions for a crack to turn (1) is not satisfied (a crack appears). The stresses do not increase instantaneously. There exists a definite edge zone where the stresses increase gradually, for which high compression stresses along the sheet are not critical. This agrees with practical experience in cutting. It is known that problems are very rarely encountered when the edges of a sheet with PLF or DLF format are trimmed along the pull line.

Cutting Losses

It has been determined experimentally that in the case of cutting losses a crack starts to propagate uncontrollably at a definite (hardly perceptible) time after the roller has passed (deposition of scratch). Thus, the problem reduces to determining the critical tensile stress for glass with a cut — a groove with a subcritical microcrack normal to the surface of the sheet ("median" or "main" crack).

This quantity was determined by modeling with the software ANSYS Structural Ver. 14.0.

For the model a subcritical microcrack was represented as a thin mathematical cut with a variable depth, loaded far from the crack by stresses parallel to the x axis. The variation of the stresses along the height of the sheet was given by two model distributions:

$$\sigma(z) = 1, \quad -\frac{t}{2} \le z \le \frac{t}{2},$$

which corresponds to pure uniaxial stretching, and

$$\sigma(z) = \frac{2z}{t}, \quad -\frac{t}{2} \le z \le \frac{t}{2},$$

which corresponds to pure bending.

The distributions were chosen so that the maximum bending stress coincided with uniform stretching.

In the model the thickness of the glass sheet was taken to be 4 mm. The crack depths were chosen to be 0.2, 0.3 and 0.4 mm, which corresponds to 5 – 10% of the sheet thickness and coincides with known estimates of the depth of the "main" crack created by the passage of a cutting roller.

After the direct problem of mechanics was solved for each type of loading and each crack size the field of displacements of the model points where the stress intensity coefficients were calculated automatically by fitting known analytical functions describing the aperture of the edges of the crack (Fig. 3).

TABLE 1. Computed Values of the Intensity Coefficients

Crack length, mm	$K_{I(II, III)}$, MPa · m$^{-0.5}$, for	
	stretching	bending
0.2	0.027261	0.025795
0.3	0.034582	0.031959
0.4	0.040345	0.036048

The computational results for the intensity coefficients are presented in Table 1. The values obtained for the intensity coefficients satisfy the well-known relation

$$K_{I(II, III)} = \sigma \sqrt{\pi l}\, Y, \qquad (4)$$

where σ is the stress, l is the crack depth and Y is a geometric factor.

These values make it possible to determine Y.

The factors Y averaged over three calculations are 1.12 for stretching and 1.03 for bending.

The real stress intensity factors can be calculated using the experimentally obtained value of the maximum bending stress at rupture.

Since measurements of the defect (main depth) depth during testing of samples were not performed, it is impossible to determine the critical intensity factor. However, the rupture stress of uniform uniaxial stretching can be determined from the ratio of the geometric factors Y

$$\sigma_c^{\mathrm{t}} = \sigma_c^{\mathrm{b}} \frac{Y^{\mathrm{b}}}{Y^{\mathrm{t}}}, \qquad (5)$$

where σ_c^{t} is the critical tensile stress, σ_c^{b} the critical bending stress, Y^{t} the computed geometric factor for stretching and Y^{b} the computed geometric factor for bending.

Evidently, the rupture stress for stretching is lower than that for bending. This means that in the presence of residual stresses approximately equal to the rupture stresses for this type of crack rupture can start immediately after the passage of a roller without raising the sheet with the breaking bar. Actually, this theoretical result explains the very existence of cutting losses (immediately after the passage of the roller).

In summary, mathematical relations making it possible to obtain the upper (stretching) and lower (compression) limits of the admissible membrane stresses were derived. The simplest, reliable method of determining the admissible shrinkage stresses is an experimental method using three-point bending.

REFERENCES

1. N. M. Pavlushkin, *Chemical Technology of Glass and Sitals* [in Russian], Stroiizdat, Moscow (1983).
2. P. D. Sarkisov, M. I. Smirnov, Yu. A. Spiridonov, and A. R. Karapetyan, "Effect of residual stresses in float glass on cutting quality," *Steklo Keram.*, No. 5, 11 – 15 (2012); P. D. Sarkisov, M. I. Smirnov, Yu. A. Spiridonov, and A. R. Karapetyan, "Effect of residual stresses in float glass on cutting quality," *Glass Ceram.*, **69**(5 – 6), 149 – 152 (2012).
3. O. S. Narayanaswamy, "Stress generation and redistribution in annealing and cutting of glass ribbon," in: *18th International Congress on Glass*, San Francisco (1998).
4. A. I. Zaitsev, *Bending of Thin Plates: Methodological Instructions for Solving Problems of Elasticity Theory* [in Russian], AGTU, Arkhangel'sk (1998).
5. S. M. Solntsev and E. M. Morozov, *Fracture of Glass* [in Russian], Mashinostroenie, Moscow (1978).